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ORIGINAL PAPER

Walking through volcanic mud: the 2,100 year-old Acahualinca footprints (Nicaragua) II: the Acahualinca people, environmental conditions and motivation

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Abstract We analyzed bare human footprints in Holocene tuff preserved in two pits in the Acahualinca barrio in the northern outskirts of Managua (Nicaragua). Lithology, volcanology, and age of the deposits are discussed in a companion paper (Schmincke et al. Bull Volcanol doi: 10.1007/s00445-008-0235-9, 2008). The footprint layer occurs within a series of rapidly accumulated basaltic–andesitic tephra that is regionally correlated to the Masaya Triple Layer Tephra. The people were probably trying to escape from a powerful volcanic eruption at Masaya Caldera 20 km farther south that occurred at 2.1 ka BP. We subdivided the swath of footprints, up to 5.6 m wide, in the northern pit (Pit I) into (1) a central group of footprints made by about six individuals, the total number being difficult to determine because people walked in each other's footsteps one behind the other and (2) two marginal groups on either side of the central group with more widely spaced tracks. The western band comprises tracks of three adjacent individuals and an isolated single footprint farther out. The eastern marginal area comprises an inner band of deep footprints made by three individuals and, farther out, three clearly separated individuals. We estimate the total number of people as 15–16. In the southern narrow and smaller pit (Pit II), we recognize tracks of ca. 12 individuals, no doubt made by the same group. The group represented in both pits probably comprised male and female adults, teenagers and children based on differences in length of footprints and of strides and depth of footprints made in the soft wet ash. The smallest footprints (probably made by children) occur in the central group, where protection was most effective. The footprint layer is composed of a lower 5–15-cm thick, coarse-grained vesicle tuff capped by a medium to fine-grained tuff up to 3 cm thick. The surface on which the people walked was muddy, and the soft ash was squeezed up on the sides of the foot imprints and between toes. Especially, deep footprints are mainly due to local thickening of the water-rich ash, multiple track use, and differences in weight of individuals. The excellent preservation of the footprints, ubiquitous mudcracks, sharp and well-preserved squeeze-ups along the margins of the tracks and toe imprints, and the absence of raindrop impressions all suggest that the eruption occurred during the dry season. The people walked at a brisk pace, as judged from the tight orientation of the swath and the length of the strides. The directions of a major erosional channel in the overlying deposits that probably debouched into Lake Managua and the band of footprints are strictly parallel, indicating that people walked together in stride along the eastern margin of a channel straight toward the lake shore, possibly a site with huts and/or boats for protection and/or escape.

Keywords Acahualinca footprints · Managua (Nicaragua) · Volcanic eruption · Footprint layer

Introduction

Footprints of hominids are rare in the geological record but harbor a wealth of information on former living conditions and behavior in stress situations when confronted with volcanic eruptions or other crises. They also provide information on the sealing conditions that allowed

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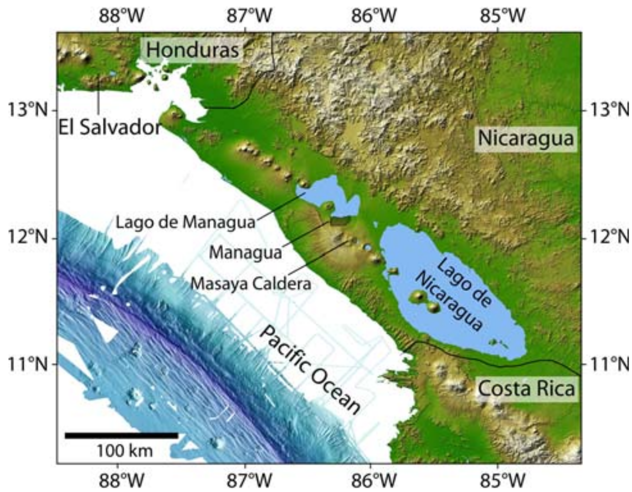

Fig. 1 Map of western Central America and adjacent Pacific Ocean, showing Managua city, Masaya Caldera, and lakes Nicaragua and Managua

preservation of tracks for thousands to millions of years. Of the handful of occurrences of preserved hominid footprints in tuffs, a few date back a few millions of years, such as those found in Laetoli (Tanzania) (3.6 Ma) (Leakey and Hay 1979; Hay and Leakey 1982). Most are younger or even historic (Kīlauea 1790: Jaggar 1921; Swanson and Christiansen 1973; Swanson 2008; Swanson and Rausch 2008), but none is as spectacularly preserved as those at Acahualinca on the northern outskirts of Managua, Nicaragua (Fig. 1).

Flint (1884) discovered the ancient footprints in the general area of Acahualinca (Fig. 2). Brinton (1887) et al. took issue with some of Flint's reports and conclusions, including his extreme age estimates of the footprints of 50,000 to perhaps 200,000 years. Footprints, probably in the same layer, were also found in other quarries up to 1.5 km farther south, where massive tuffs above the footprint layer were widely quarried for building stone. The large number of prints led Crawford (1891) to suggest that people were congregated in large towns or cities of 30,000 or more inhabitants. Richardson (1941) and Richardson and Ruppert (1942) carried out the first extensive and systematic excavations of the site in 1941, laying the foundation for the present pits. Tracks of a peccary, deer, otter, lizard, and birds were found next to the human footprints and also in adjacent areas, especially in the drainage ditch known as El Cauce (Williams 1952). In El Recreo, ca. 2.5 km to the south, tracks of a bison were found in probably the same layer. Williams (1952), who studied the diggings in 1941 and 1949, presented a more detailed volcanological study of the volcaniclastic deposits at the footprint sites. He thought that the tracks had been made in warm basaltic lahars sourced in Masaya crater, an interpretation still held by many (see below). He believed that people were running over the soft but quickly hardening surface, fleeing to their boats on the lakeshore, and he also thought that shallow imprints were made later than deep imprints at a time the mud had become firmer. Other authors thought that nuée ardentes (pyroclastic flows in a

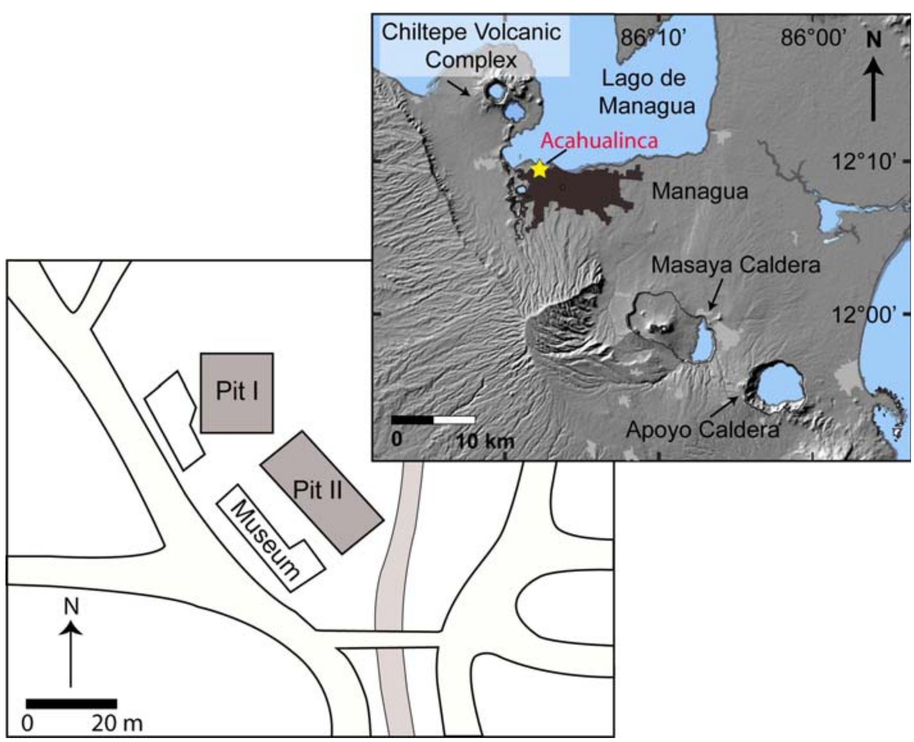

Fig. 2 Inset map: Location of the Acahualinca footprint site (*yellow star*) in the Acahualinca barrio, northern Managua city, close to Lago de Managua. Detailed map of the Acahualinca museum and footprint site (Pit I and II). *Gray* band just east of the museum show the main drainage channel

wide sense) provided the scenario, as those are commonly believed to be the dominant cause for "volcanic catastrophes" (Anonymous). In 1989, the Nicaraguan police calculated the height of the individuals by measuring the length of their strides and estimated their weight by assessing the depth of the prints (Anonymous). The nearby excavation of Villa Tiscapa, discovered in 1996, shows clusters of shelters with foundation walls and well-preserved living surfaces still remaining from the occupation date of 600 to 1520 BC. Lange (1997) suggested that the footprints were left by an "extended family walking on the beach of Lake Managua (and probably gathering and collecting plants, and perhaps fishing), somewhere around 4000 BC, and not a group fleeing a natural disaster as had sometimes been suggested in the past".

Following their original discovery, discussions centered mostly on the probable age of the footprints, the nature of the footprint layer, and the question of whether the people tried to escape from a volcanic eruption or were just walking about. None of these questions can be answered without painstaking analyses. Following an account of the stratigraphy, volcanology, chemical and mineralogical composition, and age of the deposits (Schmincke et al. 2008), we here analyze the footprint surface in more detail and with a different focus. We document the number of people involved, lengths of imprints, stride, and the probable age spectrum of the group of people who walked across the surface of freshly fallen wet tephra. We discuss the reasons for the exceptional preservation of the footprints and speculate on the action and motivation of the people who made the footprints. While, we have marshaled evidence to answer some of the issues, many questions remain. Preliminary work was reported by Schmincke et al. (2005, 2007).

Comparison with other human footprints in tuffs

The most famous ancient human footprints are those of Laetoli in Tansania, their age having been determined as 3.6 Ma (Leakey and Hay 1979; Hay and Leakey 1982). The tuff itself represents ash of an unusual carbonate composition (Hay 1978). Subsequent rain is believed to have provided a material consistency sufficient to allow footprints to be made. Eruptions from the same volcano a few hours or days later are thought to have quickly covered the footprint surface, allowing it to be preserved. Whether these footprints were made by hominids is, however, still debated (e.g., Meldrum 2004). At Roccamonfina volcano (Italy), human footprints associated with mammalian tracks and dated as ca. 350 ka were apparently made in the top of a pyroclastic flow deposit (Mietto et al. 2003).

The intuitive interpretation of the motivation of ancient people who left their footprints in volcanic deposits is an escape from a disastrous event. This has been the classical interpretation of the famous Polynesian footprints on the dry southern slope of Kīlauea Volcano, first proposed by Jaggar (1921) as dating from an eruption in 1790. The footprints on the southern flank of Kīlauea were made in wet ash rich in accretionary lapilli resulting from phreatomagmatic eruptions resembling, but slightly coarser-grained than, those at Acahualinca. However, Jaggar noted that there are at least two generations of footprints at Kīlauea, and recent work indicates that the tracks reflect old traditional trails used by the Polynesians as well as off-trail excursions by individuals and groups (Moniz-Nakamura in press). On-going work (Swanson and Rausch 2008) indicates that the younger generation of footprints was indeed made in 1790, but that a correlation to a band of warriors, as Jaggar suggested, is ambiguous. Of all the ancient footprints described so far, those at Acahualinca are arguably the best preserved. The time is ripe for anthropologists to take a closer look.

The footprint surfaces

Several hundred individual footprints are exposed in two roofed pits in a museum, part of the National Museum of Nicaragua, on the northern outskirts of Managua, close to Lake Managua (Figs. 1, 2). The larger northern pit (Pit I) measures 11.5 × 9.3 m, the smaller southern pit (Pit II) 19 × 3 m. The 4-m-high walls of the main pit (Pit I) expose several lithostratigraphic units (Figs. 3, 4). The same group of people most likely made the footprints in both pits, which are separated from each other by an unexcavated stretch 6.6 m wide.

A major aspect of the band of footprints is the contrast between a central group of many overlapping footprints

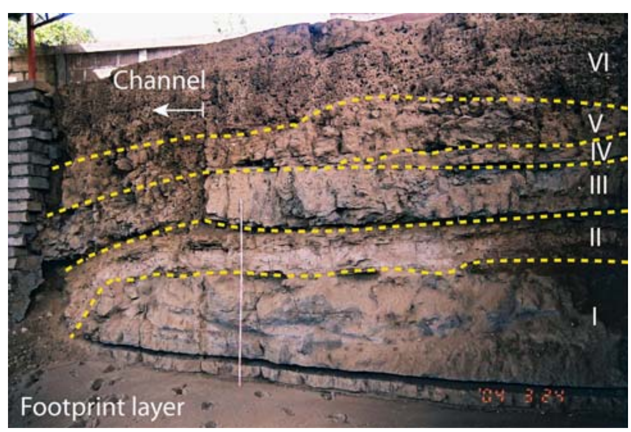

Fig. 3 Northern wall of Acahualinca Pit I, showing the stratigraphy (Unit I–Unit VI and the footprint layer) described by Schmincke et al. (2008). Eastern margin of the channel on left side of photograph; *arrow* points toward channel axis. Scale 2 m

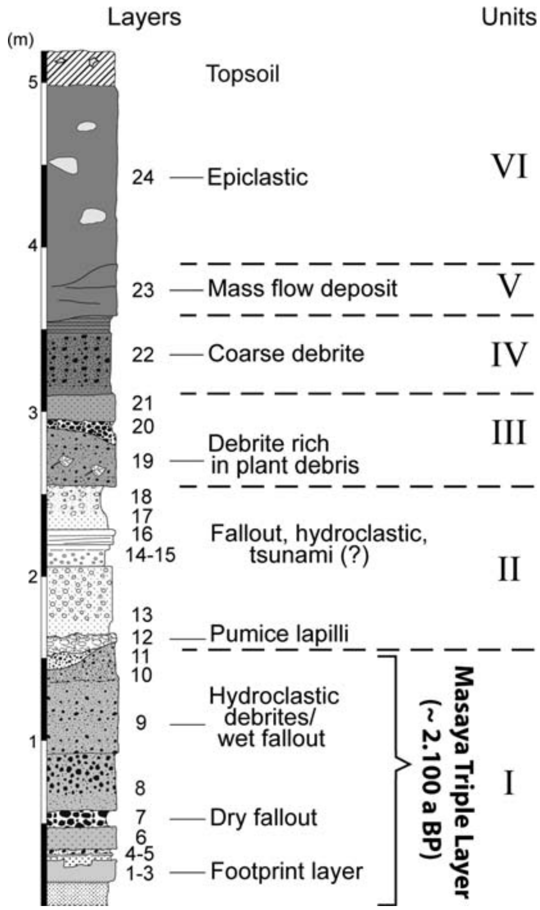

Fig. 4 Stratigraphic section of Acahualinca Pit I

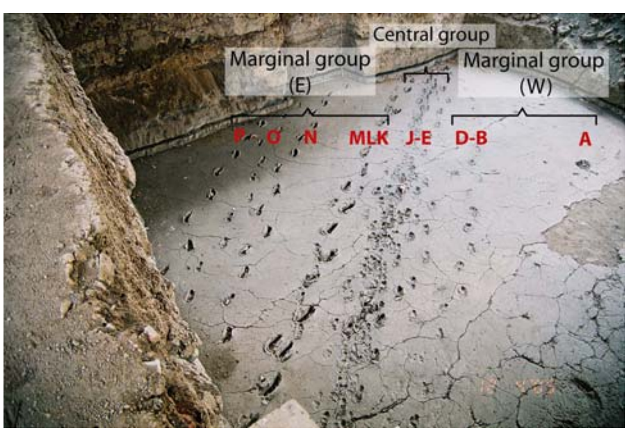

Fig. 5 Overview of footprint swath in Pit I showing the central and two marginal groups. Individual tracks are labeled A to P

and marginal groups of footprints, where tracks of individuals are mostly easy to characterize. We gave letters to individual tracks, where they can be separated (Fig. 5) and grouped into several tracks where appropriate. The volcanic deposits just below and above the footprint surface (FS; the actual bed is termed footprint layer FL, our lithologic unit I (Fig. 4)) are composed mostly of massive basaltic–andesitic tephra layers, interpreted to represent separate pulses of a phreatomagmatic eruption that may have lasted several weeks to months.

We address below several questions posed by the footprints. How many individuals made up the group? What are the gender and age of the people? What were the physical properties of the surface on which the people made their imprints? Why the surface is well-preserved? What were the environmental boundary conditions during their walk and until the footprint surface became covered with the next tephra layer? Where did the people come from, and where were they going?

Number of tracks and individuals

Pit I

A swath of tracks all heading strictly northwestward run obliquely across the floor in the northeastern half of the pit (Fig. 5). This is the reason why the number of tracks for individual B in this pit is high (22 footprints for a total track length of 11.5 m). The length of tracks of the outermost person (P) at the northeastern end, on the other hand, is only about 2 m. Some impressions exceed 10 cm in depth, but most are shallower. The swath of footprints in the center is roughly 5 m wide, the greatest width being 5.6 m.

The total number of people is 15–16, more than previous estimates of 10 (Anonymous), a figure we adopted in an early abstract prior to detailed analysis (Schmincke et al. 2005). An independent check by several members of our group also suggests that about 15–16 people walked across the surface in Pit I. Obviously, additional people walking outside of the outcrop area could have been part of the group. However, the general symmetry of the swath of tracks is suggestive evidence that the actual size of the group was roughly as represented by the tracks. Animals (deers and birds) made minor imprints after the human tracks (see below). The surface of the deposit is slightly undulating but generally very smooth and fairly flat except for a low ridge running parallel to a large channel axis (Schmincke et al. 2008) about halfway between the footprint swath and the western wall (Fig. 5).

We distinguish 15–16 different individuals (A to P) but emphasize that the exact number in the central group is uncertain. The highest number of footprints (22) was counted for individual B. Excluding the central group, there are 10 clearly discernable individual tracks, in one case reused by two or three people. The southwestern group of four tracks (A–D) includes the single outermost footprint (A) and three clearly separate tracks (B, C, D) west of the central group. The outermost footprints—some of the best preserved—are apparently of a young person because of the small size of the footprints (length 19.4 cm). The number of people in the central band is probably 5 (F, G, H, I, J) judging from parallel or sub-parallel footprints overlapping each other, with one outlier to the left (E). The number of individuals in the central group is, however, difficult to determine exactly, because of the almost complete overlap of the tracks. A north-eastern group of six tracks consists of an outer group of three tracks (N, O, P), the central individual with shallow imprints and the outer ones with locally more than 10-cm deep imprints, suggesting that the middle person was younger or at least of lesser weight than the two outer ones (or walked later, after the ash had dried more completely). An inner subgroup (K, L, and M) consists of a wide side (northeastern branch) with one large and one overlapping smaller footprint, where two people in part used the same footprint.

The marginal groups

Three people walked outside the central band on both sides. On the left (west) side, B and C (A has only one impression) have mostly strides of 45–60 cm, but the most extreme stride, >80 cm, belonged to individual C in the western group. Larger (older?) people, especially on the northeastern side, apparently walked outside the main track, possibly because they protected the central group. Some individuals of the western group were smaller (teenagers?) than those of the northeastern group (adults?), as shown by significant differences in the length of footprints and strides and, in part, also of depth of tracks. Person B was separated from person C by approximately 60 cm, and person A from person B by about 90 cm. The distance between person A and the central band is approximately 2 m, and the distance from the central band to the most northeasterly person is about 2.9 m.

The northeastern group of tracks was made by an exterior subgroup of three people (N, O, P) walking within a 40 cm band, separated by a footprint-free area approximately 80 cm wide from three people (K, L, M) who used each other's footsteps. The distance to the central group is up to 50 cm, but locally the double track closely approaches the central group.

The central group

The central group consists of one person (J), who walked to the right and can be distinguished in several places from the central group of probably four people, and one person (E), who walked about 30 cm left of the main band. If the central number of four individuals is correct, a total of six individuals walked in the central group. The lengths of the footsteps, both in the left and right (west and east) outliers, are all between 22 and 24 cm, so at least these people were of similar size. Footprints in the track east of the western outlier were deepened by one person walking in the tracks of another.

Pit II

Pit II shows (1) a western marginal group of one outer person and two inner individuals, who mostly but not always used each other's steps in a complex manner. Beginning in the southeast, the two individuals left very clear track ways, walking side by side to form some of the best impressions at the Acahualinca site (Fig. 6). About halfway along the track swath, however, the muddy layer is especially thick, and deep imprints were made practically by everybody (see below). At this point, the easternmost person of this group turned to the right, approaching a double track coming from the main group. About 2 m north of this junction, the far (westernmost) person of the three-person group moved away from the central group (*solid arrow* in Fig. 6), forming a clean single track. About 0.5 m farther east, one person from the central group, also walking westward, used the tracks of the second individual,

Fig. 6 Footprint swath in Pit II comprising about 12 individuals. *Arrows* show slight changes in direction of tracks (see text)

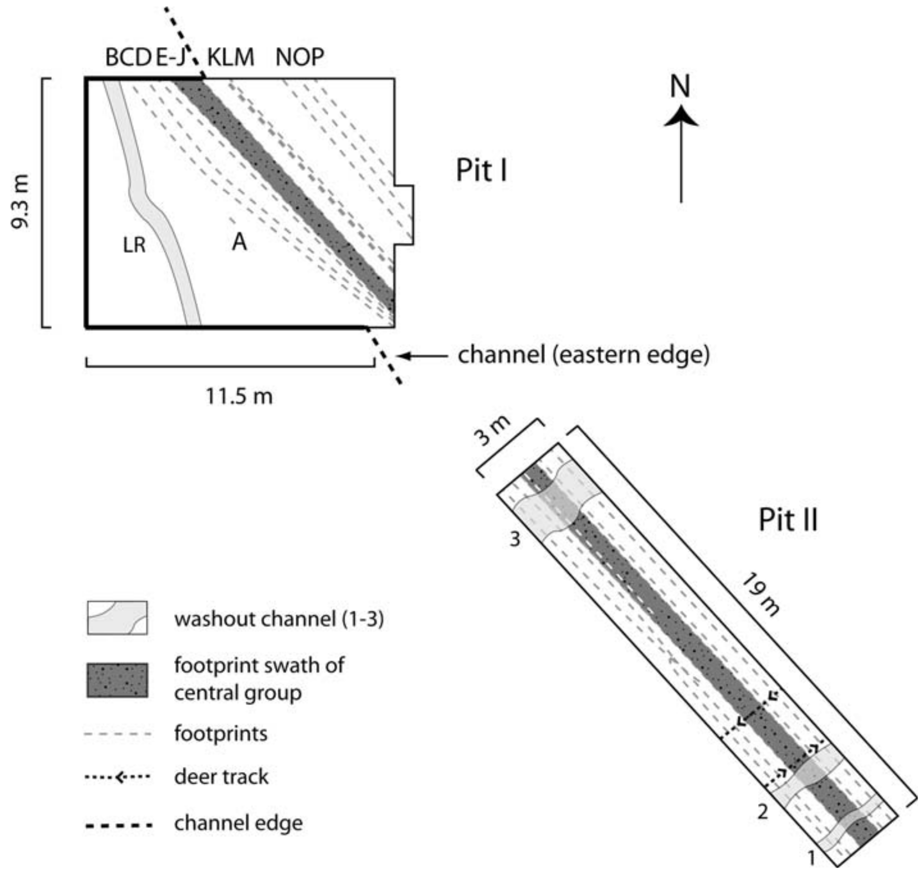

Fig. 7 Map of Pits I and II, showing footprint swath correlation between both pits. Footprints are shown by *grayish dashed lines*. The total number of people in Pit I is about 15–16 (A–P), while in Pit II tracks of 12 individuals can be distinguished from each other. Pit II is crossed by three washout channels (1–3) and two deer tracks perpendicular to the footprint swath. Individuals in Pit I walked parallel to a large NW–SE oriented erosional channel, the eastern edge of which is shown by *black dashed lines* outside the Pit I box. LR is low ridge

creating a double track trace (*dashed arrow* in Fig. 6). Two other individuals going toward the central band can be clearly distinguished from each other in the north but not well in the south. In summary, there are 5 clear tracks west of the central group (Figs. 6, 7).

The central group comprises at least three, possibly five, people, the exact number is impossible to determine because the tracks overlap almost completely.

The eastern marginal group has one clear track on its outer side and a second with deeper imprints closer to the central group. The outermost person made longer strides than the one toward the center, who, however, has much deeper imprints. Possibly, this individual carried a load, because it seems unlikely that the thickness of the ash layer differed so drastically within 50 cm. Alternatively, what looks like the track of one person could represent the track of two individuals, who used exactly the same footsteps.

In summary, five people in Pit II formed the western subgroup of tracks, two people the eastern subgroup, and three to five people were responsible for the tracks in the central band. In other words, about 12 people made the footprint band in Pit II. The limited width of Pit II makes it likely that more people walked farther east as in Pit I, where we have counted tracks of 15–16 individuals (Figs. 5–7).

Length of strides and footprints, age spectrum and gender of people

Many of the footprints have well-developed ball and heel impressions with a raised central area, evidence that their feet were arched. Using a commonly accepted foot-length/stature ratio of 15% (Giles and Vallandigham 1991), we estimate the height of the people to have ranged mostly from 1.29 to 1.58 m.

We subdivided the tracks based on length of footprints and strides as measured along three tracks in both pits and distinguished at least three size groups of footprints (Table 1, Figs. 8, 9). Depth of imprints and length of individual footprints are generally well correlated. We tentatively distinguish three types of individuals: male and female adults, and teenagers/children. Our interpretation of individuals as children and teenagers is based on smaller lengths of footprints (15–16 cm and 19–20 cm, respectively) and strides (Fig. 8). Based on these criteria, we identify between two and four individual tracks made by teenagers. We tentatively attribute the following tracks in Pit I to teenagers: A, B, F (?) and G (?). Clear recognition of additional teenagers in the central group was impossible. Still smaller footprints in the central group suggest that children may have walked in the more protected center of

Table 1 Lengths of footprints and of strides from individuals B, C, and O in Acahualinca Pit I

Name of individual	B	C	Madame "O"
Length of footprint (cm)	19;18;20;19;20;20;19.5	24;24;24;23.5;23.5;22 24.5;24;24.5;23;23	22;22;21.5;22.5;22;21.5 23;23;23.5;22;23
Average length of footprint (cm)	19.36	23.64	22.36
Length of strides	37.5;41;48;48;43;48;51;50	52;56;54;55;58;54;56	55;54;55;59;54;52.5
From heel to heel (cm)	45;50;48;45;45;46;47;45;45	88;75;59;61;56;60	53;56;55.5;58;53
Average length of strides from heel to heel (cm)	46.03	60.31	55
Height of individual (m)	1.29	1.58	1.49

Height of individuals is calculated based on footprint/stature ratio of 15% (Giles and Vallandigham (1991))

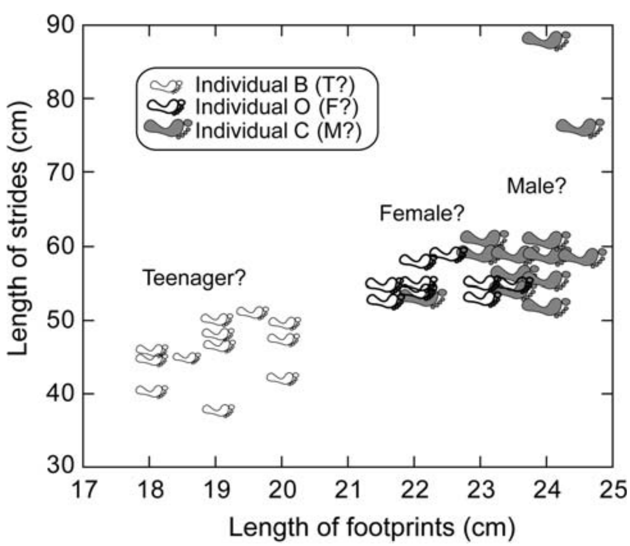

Fig. 8 Correlation between length of individual footprints and of strides in Acahualinca Pit I. *T* teenager, *F* female, *M* male

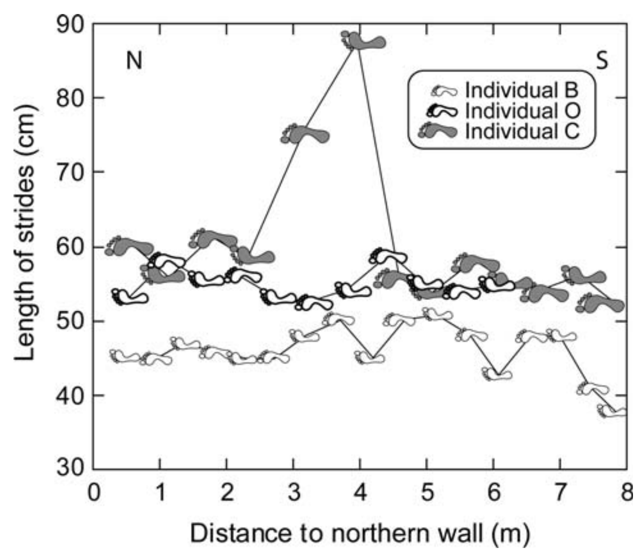

Fig. 9 Change of length of strides (cm) from southeast to northwest (channel-margin) in Acahualinca Pit I

the group, but the imprints are too blurred for a precise interpretation. Distinction between male and female individuals is of course entirely speculative. We suggest that individuals N and P in the northeastern subgroup were males based on size and depth of imprint and length of stride, while person O ("Madame O") in between may have been a woman (?). Our interpretation of individuals as men (though relatively small footprints) is based on the fact that indigenous Central American people are known to have been short compared to European standards.

A major aspect of the strides is a significant change in length in several tracks toward the north (Fig. 9). In other words, several people appear to have reduced their stride and perhaps speed of walking. We suggest—among many options—two different reasons for this apparent change. For one, the group may have slowed down because they were approaching something of interest, such as their boats or huts. Or, they may have slowed because they had to cross a channel filled with water. This speculation receives some plausibility because of the interruption of the Footprint Layer (FL) by a channel-like feature now filled with dirt that runs at a small angle to the band of footprints (Schmincke et al. 2008).

Animal tracks and impressions of sticks

The FL contains tracks of animals (such as, otter and turtle), some recognized by earlier workers (summarized by Williams 1952). In Pit II, a deer crossed the footstep trackway about 4 m north of the southern boundary of the pit and close to the second washout, walking from southwest to northeast. A young deer walking in the opposite direction (from northeast to southwest) made a second smaller track about 3 m north of the second washout (Figs. 7, 10). A deer that walked parallel to the people made a third track, about 2 m to the north in Pit II. Near the main track where a very clear deer imprint is present, there are also bird tracks. The deers probably walked across the trail after the people had crossed it. Slightly washed out imprints of deer print also occur in Pit I.

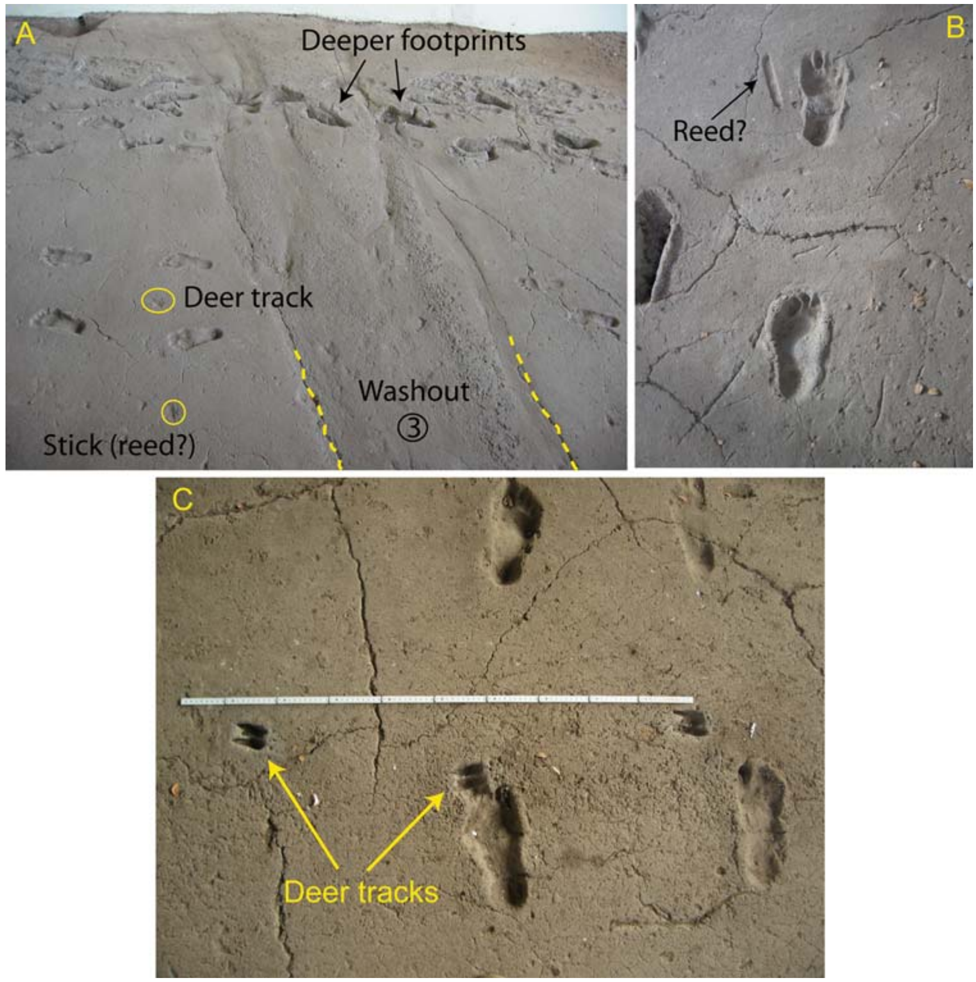

Fig. 10 **a** Deer tracks and imprints of reed (?) in Pit II. Note NE–SW-oriented washout. Footprints are deeper in the upper part of the photograph, probably because the muddy tephra was locally thicker; **b** Imprints of <5-mm wide sticks (reed?); **c** Tracks of a deer (about 7 cm long) that walked westward at right angle to the Acahualinca trackway; scale 1 m

Most nonhuman impressions, however, are of small sticks, some more than 10 cm long (Fig. 10). These impressions are concentrated near people with the deepest tracks. Such deep imprints could be due to people carrying a load, as previously suggested (Williams 1952; Bryan 1973), and this may have been the reason why these individuals are at a distance from the central group. They might have carried other people (little children or elderly adults unable to walk). Or, perhaps, these people were carrying a heavy load from which small sticks broke off and fell in the "mud". The abundance of stick imprints may also reflect the action of wind, possibly aggravated by turbulent atmospheric conditions connected with a big eruption. Possible loads include:

(1) Firewood: This is unlikely, because the imprints of sticks are <5-mm wide and too regular to represent branches of trees. Moreover, there is no evidence that trees were growing in this area.
(2) Materials such as bamboo, or the more fragile reed, which they could have used to make their huts or boats, both possibly having been made from the same material. This material must have been dry, however, to allow pieces to fall down as sticks. Availability of dry reed near the lakeshore fits our conclusion that the tracks were made during the dry season (see below).
(3) Alternatively, an adult could have carried something that was already made, such as boats made of reed or another type of plant that had been stored on higher ground and were carried to the lake.

Physical properties of the footprint layer

Favorable physical properties of the FL were a prerequisite for the quality and details of the footprints to be made—and preserved. The wet ash in general was squeezed out but did not flow back into the imprints. In other words, the wet ash had sufficient strength (high viscosity) that the material oozed from the ground remained in place and sometimes hardened in complicated forms due to the nature of the squeeze ups. The few millimeters of muddy material capping the coarser ash of the FL was locally squeezed up 4 cm alongside their feet. The material was thus, easily deformable, despite its relatively coarse grain size. Moreover, the main, coarser-grained ash below the fine-grained top layer is now a veritable vesicle tuff, a property that explains some of the pliability of the ground over which the people walked.

The freshly fallen ash was moderately stiff, viscous mud, resembling, but mushier than, modeling clay, soft enough for clear imprints to be made but viscous enough for the preservation of details, such as distinct toe impressions and squeeze-ups. We estimate that the ash had a water content of ca. 20–30 wt.%. Had it been water-rich slurry, no clear footprints would have remained. On the other hand, had the ash been much coarser grained and mostly dried, no or only vague imprints could have been made.

Depth of footprints

One striking aspect of the footprints is the pronounced differences in their depth, some >10 cm deep, and the height and thickness of raised rims (squeeze-outs) (Figs. 11, 12, and 13). We propose five reasons that could explain these differences; three are supported by convincing evidence, depending on the particular location:

(a) The original thickness of the muddy ash FL was uneven, generally ranging from about 1 to 2 cm but to >10 cm in some areas.
(b) The footprints were made by people of different weight (men, women, teenagers, and children).
(c) Deep imprints represent multiple impressions by people walking one behind the other.

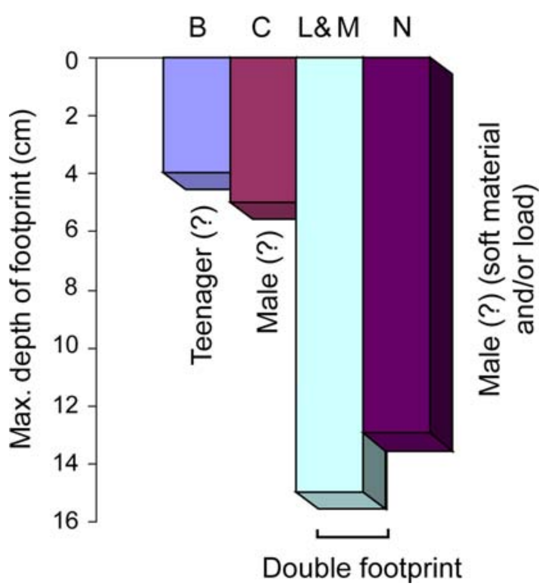

Fig. 11 Maximum depth of footprints (cm) for individuals B, C, L, M and N in Pit I

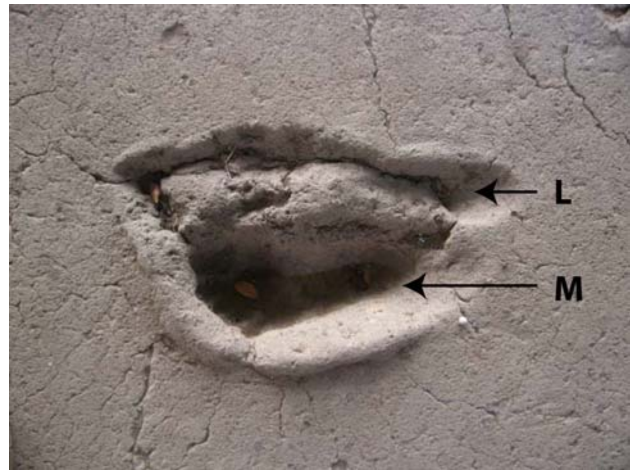

Fig. 12 Individual M walked so close to individual L that the earlier footprint was deepened. Depth of footprint M is 15 cm (Pit I)

Fig. 13 Contrast between deep (*center of photograph*) and shallow (*lower part*) footprints. The shallow prints are smaller and were probably made by younger individual (Pit II)

(d) People carrying a heavy load made deeper impressions.
(e) The timing of the footprints within the group varied considerably, the deep impressions made early in soggy, pliable ash and the shallow footprints later, when the mud had partly dried.

Hypothesis (a) explains very deep impressions in the middle part of Pit II, where all tracks but one is several centimeters deep (Fig. 13). Here, the thickness of the FL ranges significantly from 1–2 cm to >10 cm, probably because of the adjustment of the low-viscosity, coarse to very fine-grained ash to the local surface relief. The two outermost tracks in the western band of Pit II are shallow in the northern part of the pit but deep in the central part, where the thickness of the layer was probably at least 15 cm. This clearly shows that significant differences in the thickness of the FL are the main control for these situations. Footprints in Pit II were blurred or eroded away in three washout channels because water was retreating from the surface (Figs. 6, 7, 10a). The wet ash must still have been soft enough to be washed away, so the erosion must have happened soon after the footprints were made.

Hypothesis (b) can explain several contrasts in footprint depths in Pit I. For example, the relatively shallow imprints of the western group (especially for individual C) clearly coincide with relatively small sizes of footprints and smaller lengths of strides, suggesting that tracks A–D were made by lighter people, possibly teenagers. A second clear example is the contrast between tracks N, O, and P of the eastern group, where a similar correlation between depth of imprints and size of footprints hold, our tentative interpretation being that N and P were made by men and O by a woman (see above). Similar relationships between depth of footprint and size of footprint and stride are also found in Pit II.

Clear evidence suggests that hypothesis (c) is an additional, if not sole, cause of particularly deep impressions. The most striking examples are the deep imprints of the KLM group (Pit I), some of the 16 footprints along this trackway made by up to three people walking behind one another (Figs. 11, 12). The rims of these deep imprints are the highest in Pit I.

Hypothesis (d) is a possibility, especially for some deep tracks outside the central group (e.g., N and P, Pit I), since the reason for people to walk there may have been the load they carried. We lack evidence for verifying this possibility, however. Another example is the contrast between the two outer trackways on the eastern group of footprints in Pit II; the outermost mostly has very small imprints, whereas all the footprints are deep near the central zone. The imprints, however, were made by the second person inside, some as deep as 15 cm. This person was apparently much heavier, possibly carrying a load, but we cannot exclude the possibility that two people walked exactly in each other's steps.

Williams (1952) suggested that the shallow imprints were made later than the others, after the surface had dried and was no longer soggy (Hypothesis e). This explanation is unlikely, however. Several tracks show both shallow and deep imprints, apparently because of local thickening of the muddy layer. The overall symmetric organization of the track swath suggests to us that the people walked as a group. Finally, almost all cases of contrasting depths of imprints can be explained satisfactorily by hypotheses (a), (b), or (c).

Season

Williams (1952) suggested that the tracks were made during the rainy season, torrential rains generating mudflows that, according to Williams, make up what is called here the upper unit I deposits and the FL itself (Fig. 4). We think that the eruption took place during the dry season (approximately October to May) for several independent lines of evidence.

(1) The footprint surface is thoroughly mud-cracked, a dry season being in harmony with quick drying of the mud. (2) The footprint surface shows no signs of rain, such as raindrop impressions that might have formed in the soft mud coating (Schmincke et al. 2008). (3) The sharp boundaries between the different layers of unit I (Schmincke et al. 2008) imply absence of erosion between different deposits of the eruption. (4) The mud was relatively viscous, because all the sharp and well-preserved squeeze-ups stayed in place and did not flow back into the footprints. (5) The prevailing wind direction affecting the ash distribution of the initial footprint layer, in combination with the likely source area of this eruption (Masaya caldera) (Schmincke et al. 2008), also suggest deposition in the dry season, when winds are from the N–NE at 8–12 km height in the troposphere (Kutterolf et al. 2007).

Preservation of footprints

There are several prerequisites for preserving footprints:

- A footprint layer: must not only be soft but also pliable enough for the footprints to remain for a critical period of time.
- A layer must also be of a finite thickness (a few centimeters) and preferably overlie harder ground to allow the people to make their way without sinking too deeply. The physical consistency may be due to deposition of wet ash, as we infer for Acahualinca, or rain falling on dry ash, as postulated by Hay (1978) for Laetoli.
- An essential requirement for preservation is a rapid drying of the footprint-bearing ash before erosional processes (e.g. heavy rain) occur. Our interpretation that the Acahualinca footprints were made during the dry season (see above) infers that the sun probably dried the ash layer quickly making possible preservation for months to years.
- A cover by another tephra layer, or, in general, by a deposit that does not involve eroding of the footprint surface (as windblown sand covers many footprints at Kilauea) soon enough to prevent rain or other environmental conditions from destroying the tracks is

indispensable for the long-term preservation. Such tephra layers may originate as fallout and often follow each other in quick succession on higher ground away from major channels, where most erosion takes place. This evidence is detailed in Schmincke et al. (2008) and has also been argued for by Williams (1952).

Washouts

The band of footprints in Pit II is crossed at three places by conspicuous washout channels up to 2 m wide and several centimeters deep; the largest and deepest occur at the northern end of the narrow pit (Figs. 6, 7, 10a). These washouts were carved after the group of people had walked across the wet and muddy tephra surface. Currents were strong enough to largely remove the actual 1–3 cm thick, fine-grained, slightly cohesive wet top of the FL and erode channels up to 5 cm deep. There is no evidence for wholesale energetic flooding of the track surface, however; water was concentrated in the three channels at least during backflow, although gentle smoothing of the footprint surface may have occurred, judging from the smooth surface. The very slight northeastward inclination in Pit II of the FL suggests that water was flowing in that direction.

We envision two possibilities for the origin of the washouts. They could reflect retreating water that had advanced in narrow tongues from Lake Managua and was flowing back in the same narrow channels. The northernmost washout shows well developed "bath tub" rings. Whether the water currents that made the washouts were in some way due to dynamic processes related to the eruption (temporary heaving of the ground, for example) is unknown. Another, and probably more likely, possibility is that the small floods that caused the washouts represent overspills of the channel to the west (Schmincke et al. 2008). In any case, a reasonably strong current must have carved the deep and wide northernmost washout channel.

We cannot discount the possibility that the washouts were caused by runoff of heavy rain concentrated in some outlets. However, if this was the case, we would expect to see some fine ash washed by water into the footprints and evidence of small rivulets on the ground. The well sorted ash on top of the FL, locally consisting of a fine ash topped by coarser ash, might represent redistributed ash.

Discussion

The Acahualinca group

What is the significance of the size of the group? Why did the people walk in a swath some 5 m wide? How fast did they walk? Why did they change direction? Where did they come from? Where were they headed? Answers to these questions must necessarily be speculative. We hope to present sufficient data and arguments for archeologists to attempt a more in-depth interpretation of some of the questions posed above.

None of the published reports on the footprints following the discovery by Flint (1884) comments in detail on the number of tracks, their overall arrangement, and direction. We are impressed by the remarkable symmetry of the swaths in both pits, with one central and two marginal groups of tracks made by a group of 15–16 people. Was this a large family? A group of people that lived together? A small settlement?

Williams (1952) suggested that people who made the shallow imprints walked across the surface after it was drier than when the deeper prints were made (see above). We showed above that individual tracks with shallow imprints were generally made by smaller, possibly younger people (teenagers?). Moreover, a person who left shallow imprints in one place made deep imprints in an area, where the muddy footprint layer was significantly thicker. Finally, the tight and symmetrically organized group and the strict direction of the swath in both pits, in parallel with, and just east of, a drainage channel suggest to us that the people did form a group all walking together toward a site at Lake Managua with a clear goal.

The people were not running, because most footprints show the imprint of the entire foot (ball and heel), not only the ball. Moreover, running on a muddy surface is physically difficult. On the other hand, we think that the group walked at a brisk pace, judging from (1) the tight and strict orientation of the swath of footprints in both pits over a total length of at least 25 m and (2) the length of strides. The people were obviously determined to go somewhere. However, the very deep impression that the second person (or, in the northern part of Pit I, the two people who generally used the same track) made, with the front part of the foot deeper than the back part, could mean an accelerated pace, almost running. Alternatively, it could mean that the people were "digging in" with the front of each foot as they crossed the slippery, difficult mud surface. The distance to the shore of lake Managua was probably <500 m, about the present distance, and the people walked toward the lake.

About halfway across the deeper "mud" in Pit II, the westernmost person and the central band changed direction abruptly toward the northwest, while the eastern outlier changed direction only slightly. In other words, the people were closer together before they changed direction. The westernmost individual and the central group changed direction at the same point, as did the person just east of the central band who left a deep impression. This suggests that the people walked together until everybody sank in and then slightly veered toward the northwest. We suggest two possible reasons:

- The people spotted their goal (channel (?), boats (?), and huts (?)).
- Changing direction would keep them out of the deep "mud".

Difficult to explain is that the direction the people walked is at right angles to the washouts in Pit II. Most likely, either the coastline or the channel was not straight.

At least one person in each pit walked a little outside on the left side, perhaps because it was too crowded in the middle if the people walked together.

Were the people escaping a volcanic eruption or did they go about their daily business, as is most commonly suggested? The Nicaraguan police (Anonymous), as well as archeologists (e.g., Lange (1997)), tried to dispel the "more sensational" hypothesis that the people were fleeing from a menacing volcanic eruption (Anonymous). They postulated instead that the people walked in a relaxed manner collecting food along the beach. We can marshal several arguments for our interpretation that the footprints reflect the attempt of the Acahualinca people to escape from a powerful volcanic eruption—a hypothesis discounted by most authors, though Williams (1952) earlier thought that the people were fleeing a volcanic eruption.

- Most importantly, the FL is the first of several tephra layers that reflect one major eruptive period of finite but short duration, lasting perhaps weeks or months. The time interval between deposition of the vesicle tuff and its cover of fine-grained wet ash—the actual footprint layer—and the journey of the Acahualinca people was short (hours? or days?). This is persuasive evidence that the people had just experienced a fall of ash from an explosive eruption, perhaps hearing noises from Masaya crater to the south, seeing an eruption column, and smelling sulfurous fume.
- The footprint surface was covered by the ash of the next eruptive pulse, deposited most likely only few hours (or days?) later. The FL surface had slightly dried, suggesting a lull in the ash fall. The time interval between deposition of the FL and the overlying ash must have been short, however, because there are no signs of erosion and the overlying ash drapes over the squeezed-up mud bordering the imprints. On the other hand, the presence of mud cracks indicates enough time (hours? or days?) to dry the squeezed-up mud and part of the overall surface.
- The footprint surface was flat and smooth, with a base of coarse-grained basaltic ash and fine lapilli at least 10 cm thick covered with a layer of wet ash mostly <1 cm thick. In other words, the FL represented freshly fallen, undisturbed wet ash from an ongoing eruption rather than a tidal flat or shore area as sometimes suggested. The people were the first living beings walking across the FL.
- An impressive aspect of the footprints is their strict orientation, indicating that the people formed a tight group to get some place. The swath of footprints, parallels the direction of a major erosional channel, whose eastern edge is exposed in the western part of Pit I (Fig. 7). Most of the erosion took place after unit I deposits were laid down (Figs. 3, 4), but there is some evidence that erosion and channeling had started during deposition of unit I beds (Schmincke et al. 2008). Williams (1952) and Richardson (1941) reported more haphazard tracks in former outcrops near the lakeshore and speculated about confusion of the Acahualinca people after reaching the shore.
- The people moved in a direction away from Masaya crater, no doubt the source vent of the large eruption (Schmincke et al. 2008). Moreover, they walked at a brisk pace, as detailed above.

In summary, we suggest that the Acahualinca people probably sought refuge from a major volcanic eruption, from Masaya Caldera, about 20 km south of Acahualinca. The history of Holocene eruptions of Masaya Caldera is now well known (Freundt et al. 2006; Pérez and Freundt 2006; Kutterolf et al. 2007). Because we interpret most layers in unit I, including the FL, as products of phreatomagmatic eruptions (Schmincke et al. 2008), the vent area was likely shrouded in billowing steam and lightning-rich ash clouds, roaring noises generated by thunder and multiple explosions and, most likely, the site of persistent earthquakes. Walking briskly away from such a tumultuous place reflects basic instinct, especially since people at the time are likely to have attributed eruptions to supernatural causes.

Why were the people walking toward nearby Lake Managua? We speculate on two likely scenarios:

(1) Were they heading toward their near-shore huts or at least a place, where they could build new shelters because the roofs of their old ones had collapsed under the heavy load of the wet tephra? In this scenario, one could visualize that people had left their huts (made of reeds?), bringing new building material for huts (perhaps most likely) or boats. The hypothesis that people left their dwelling site, destroyed by an eruption, and were carrying children too young to walk (or a weak person unable to walk through the mud), makes sense in several respects. It explains why the people were walking at a brisk pace. They did not go back to fetch more building material, because the next eruption came soon, first three thin deposits in this area and then another heavy water-rich layer that must have made life miserable, may have caused deaths, and may have prompted evacuation.

The people had only minimal belongings as they headed toward the lakeshore. Their huts may have been close to the lake, convenient for fishing. One or possibly two of the persons carried an especially heavy load. The fact that one person in Pit II went farther west after the rest had stepped through the very sticky part also suggests that this person, who made the deep imprints, was carrying a load. Where they had to cross channels with possibly running water, they slowed their pace, as reflected in the reduced lengths of their strides. When ash fall resumed, another layer of wet ash and lapilli was deposited, making the area inhospitable; there is no evidence that the people did return, at least not along the exposed track. In the unlikely case that they did return it must have been under circumstances unfavorable to leave footprints.

(2) The second and probably most likely scenario we envision is that the people were headed to the moorings of their boats in order to get away from the eruption. They probably made it to their destination, because they did not backtrack.

Age of the footprint surface

Previous age estimates for the footprint surface vary widely; an age of ca. 3,000 BC (Bryan 1973) is assumed most often. The volcanology, stratigraphy, and geochemistry of deposits of Late Pleistocene and Holocene volcanic eruptions in Central Nicaragua are now known in detail (Freundt et al. 2006; Kutterolf et al. 2007, 2008; Pérez and Freundt 2006). Some of these deposits have also been dated by ^{14}C. Our evidence for correlating the FL with the Masaya Triple Layer and Masaya Caldera as the source vent has been detailed in Schmincke et al. (2008) and yields an age of 2.1 ka BP (ca. 100 BC) for the FL.

Conclusions

- At Acahualinca, a district of Managua (Nicaragua), several hundred extremely well-preserved footprints made by a group of 15–16 individuals are exposed in two pits in a roofed outdoor museum.
- The footprint layer (FL) is interpreted to represent the initial stage of a major and lasting phreatomagmatic eruption.
- The group, mostly adults but probably including some teenagers and a few children, walked across a very gently sloping unvegetated flat close to the shore of nearby ancient Lake Managua.
- The people walked parallel to, and along the eastern edge of, a southeast–northwest-oriented drainage channel whose axis probably lay west of the pit.
- The footprint swath, up to 5.6 m wide and oriented SE–NW, is roughly symmetrical, with a central group of closely spaced overlapping footprints made by about five to seven people. In this central group, individuals, probably including some children (small footprints), are difficult to separate from each other because people walked in the tracks of those ahead. The central group is bordered on both sides and in both pits by individual tracks of three to five people.
- Different depths of footprints are due to three different causes:
  (1) Contrasting weight of individuals (probably children, teenagers, women, and men);
  (2) People walking behind each other using the same track and
  (3) A local zone of thicker “mud” in Pit II.
- The tracks were probably made by one group of people walking together and not at different times.
- The people likely walked at a brisk pace toward the lakeshore trying to escape from a powerful eruption, at Masaya Caldera 20 km to the south (Schmincke et al. 2008). We speculate that the people abandoned their huts, whose roofs may have collapsed under the weight of heavy wet ash. Their goal could have been boats at the lakeshore.
- The basal phreatomagmatic unit I containing the footprint layer is correlated to the basaltic–andesitic Masaya Triple Layer erupted at Masaya Caldera ca. 2.120 ± 120 BP (Schmincke et al. 2008).
- The excellent preservation of the imprints is due to a combination of favorable circumstances including: (i) a thin layer of fine-grained freshly fallen wet ash covering a thicker, coarser, vesicle-rich ash to provide a firm base for the tracks to retain their shape; (ii) a physical consistency of the wet ash that allowed imprints to be made without causing the pliable ash to creep back into the tracks; (iii) quick hardening during the dry season; (iv) quick covering by tephra of the next pulse of the same eruption.

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